The South India Precambrian crust and shallow lithospheric mantle: Initial results from the India Deep Earth Imaging Experiment (INDEX)

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We present here the most comprehensive study of the thickness and composition (V_p/V_s ratio) of the South India Precambrian crust and the nature of shallower mantle inferred from analysis of teleseismic receiver functions from 70 broad-band seismic stations operated as a part of the India Deep Earth Imaging Experiment (INDEX). South India could be broadly divided into regions with thin crust (32–38 km) and thick crust (38–54 km). Thin crust domains include the East Dharwar Craton (EDC), Cuddapah basin and Madurai/Kerala Khondalite Block. The thicker crust domain includes the Western Dharwar Craton (WDC) and northern part of Southern Granulite Terrain. The WDC shows progressive increase in thickness from 38 km in north to 46–54 km in south, compared to an almost flat Moho beneath the EDC. Compositionally, most of the crustal domains are felsic to intermediate ($V_p/V_s \sim 1.69$ – 1.75) except the mid Archean block in the southern WDC where it is mafic ($V_p/V_s > 1.81$). Considering erosion depth in the WDC, we argue for Himalaya like ~ 70 km thick crust beneath it during the Archean. Variation in crustal thickness does not have a first-order influence on regional topography in South India and suggests significant role for the crustal composition. We also present evidence of mid-lithospheric low velocity at ~ 85 – 100 km beneath South India.

1. Introduction

Most of our knowledge about the evolution of continents and their crust and mantle signature is restricted to terrains younger than ~ 3.3 Ga due to large scale thermal modifications prior to this age. Two prominent continental crust forming events at ~ 3.3 Ga and 2.7 Ga have been reported during the Archean (de Wit *et al.* 1992; Rudnick 1995; Condie 2005; Hawkesworth and Kemp 2006; van Kranendonk 2011; Dhuime *et al.* 2012). It remains highly speculative about the process responsible for its evolution. It is widely accepted that

plate-tectonic processes operated at least as far back as 2.7 Ga (Calvert *et al.* 1995; White *et al.* 2003). Middle Archean terrains (3.6–3.0 Ga), however, lack most of the features associated with convergent plate boundaries and could possibly have evolved through melting of thick mafic crust (Davies 1992; de Wit 1998; Zegers and van Keken 2001; Nagel *et al.* 2012). Scientific opinion, however, remains divided on the process responsible for the formation and evolution of the early and middle Archean continental crust. In order to achieve comprehensive definition of the crust evolution process(es) during Precambrian and its modification

Keywords. Receiver function; crustal structure; lithosphere; craton; South India; Archean.

Figure 1. Tectonic map of South India Shield showing major geological terrains, viz., EDC – East Dharwar Craton, WDC – West Dharwar Craton, SGT – Southern Granulite Terrain, DVP – Deccan Volcanic Province, CB – Cuddapah Basin, CG – Closepet Granite, CSB – Chitradurga Schist Belt, MSZ – Moyar Shear Zone, BSZ – Bhavani Shear Zone, NKSZ – Noyil Kaveri Shear Zone, ASZ – Achankovil Shear Zone, KB – Kaladgi Basin, BB – Bhima Basin, MB – Madurai Block, KKB – Kerala Khondalite Belt. The seismic stations used in the study are shown as black (2009–2012) and blue (1998–2002) triangles.

due to recent geodynamic activity, there is need for better constraining the structure and composition of the crust and mantle, and nature of the crust–mantle interaction in geological blocks with diverse ages.

To address above issues, we initiated a long term research project *India Deep Earth Imaging Experiment (INDEX)*, supported by the Council of Scientific and Industrial Research (CSIR). The project aims at creating 3D seismic structure of the Indian crust and mantle to constrain the evolutionary mechanism along with establishing linkage with ore deposition and earthquake genesis in the region. In its first phase, the seismic imaging is

attempted for South India at various scales using data from teleseismic waveforms recorded over 70 broad-band seismographs that operated in phases during 1998–2002 and 2009–2012 (figure 1).

2. Project objectives

2.1 Origin and evolution of the Precambrian continental crust

Present day continental crust with andesitic composition has evolved from differentiation of the oceanic crust that is basaltic in nature (Rudnick

and Gao 2003; Hawkesworth and Kemp 2006). Identification and modelling of petrogenetic processes responsible for the transformation of a primitive basaltic crust to andesitic/felsic composition remains ambiguous. It is an unresolved problem related to the evolution of the continental crust through geologic time with a bearing on the mantle processes. Seismological wave velocities (V_p , V_s) and their ratio have been extensively used to characterize different rock types in the crust (Christensen 1996). The velocity ratio varies over a wide range (1.65–1.85) depending on the quartz content in it: felsic rocks have lower value compared to more mafic one. A clear definition of composition of the crust and its age relationship can help in constraining the nature of source and modelling the evolution mechanism (Gao *et al.* 1998).

Apart from composition, the other significant parameter of crust is its thickness. One of the models of crustal evolution based on global compilation of seismological measurements suggests that the mean crustal thickness, except for young orogens, is proportional to its age, with ancient crust being the thickest (Meissner 1986; Jarchow and Thompson 1989). This led to the hypothesis that the crust is thickened by repeated episodes of basaltic underplating (Nelson 1991). We hope to answer the validity of the global model for crustal evolution with respect to South India.

2.2 Nature of the deep mantle

To model the process responsible for evolution of the Earth's mantle, one of the most important caveats is to understand the nature of internal layering and its spatial variability (Anderson 2006). This is best revealed in the seismic images of the deep Earth. Cold sinking oceanic slabs show as high seismic wave velocity regions while the low velocity features are suggestive of hotter mantle (van der Hilst 2004). Gathering detailed evidence of preserved deep high/low velocity signatures within the plates in the ancient cores of the continents ('shields'), is thus essential to our understanding of the early Earth. The continental cratonic regions are underlain by a thick high velocity zone to a depth of about 250 km and suggesting primary difference from the oceanic part. We propose to map the depth of cratonic root beneath parts of South India using these seismological data and also compare and contrast with similar terrains in other parts of the globe. Further, we attempt to examine the presence of shallow mantle discontinuities that might help in hypothesizing the geodynamic processes leading to or subsequent to cratonisation of South India.

The deeper features like transition zone from 410 to 600 km depth could now be easily mapped.

Interestingly, some of the recent tomographic images suggest presence of cold sinking slabs to a depth of 1000 km beneath the southern part of India (Replumaz *et al.* 2004). The paleo-reconstructions show that seafloor spreading in the Neo-Tethys Ocean had ceased by Late Cretaceous, and that Tethyan lithosphere was being consumed along two subduction zones; one following the south Asian margin and the other, intra-oceanic, crossing the Neo-Tethys Ocean and fringing an Arabian margin still attached to East Africa. It is widely accepted that after all the Neo-Tethys lithosphere was consumed, India continued its northward drift, indenting into Asia for several hundred kilometers, and giving rise to the Himalayan orogen and the high topography of the Tibetan plateau (Besse and Courtillot 1988). As the subcontinent progressed along this collisional journey towards Asia, the subducting slabs detached from the surface continental plate and the subduction zones were overridden (Replumaz *et al.* 2004). The search for signatures of these slabs and their seismic properties can throw new light on the nature of interaction of oceanic slabs with the major Earth discontinuities, and can provide constraints on the convection models involving both thermal and chemical effects. This would also possibly answer the cause for the Indian Ocean geoid low (Spasojevic *et al.* 2010). This will be achieved by creating high resolution image of South India using these broad-band seismological measurements.

3. Geological framework and crust structure of South India

The South India Shield is an amalgamation of several crustal blocks formed by geodynamic processes operating from mid-Archean to Neo-Proterozoic time. The main geological provinces in southern India are shown in figure 1. The Dharwar craton in the southern India is an Archean continental fragment with a continuously-exposed crustal section from low-grade gneisses and greenstone basins in north to granulites in the south. It comprises of three distinct lithological units: Peninsular gneisses of tonalite-trondhjemite-granodiorite (TTG) composition dated between 3.36 and 2.7 Ga (Taylor *et al.* 1984; Meen *et al.* 1992), volcano-sedimentary greenstone belt of two distinct ages 3.3–3.1 Ga and 3.2–2.7 Ga (Peucat *et al.* 1995) and the K-rich granitoids (e.g., N–S trending Closepet granite) of age 2.5–2.6 Ga. Based on the ages and lithologies, the craton is divided into the West Dharwar Craton (WDC) and the East Dharwar Craton (EDC) with Chitradurga Schist Belt (CSB) as the boundary (Naqvi and Rogers 1996).

Table 1. Details of South India broad-band seismograph network stations, Moho depth (H), V_p/V_s ratio with bootstrap errors, Poisson's ratio (σ) computed from H - k analysis, number of receiver functions (N_{RF}) used in the analysis.

Stn. code	Lat. (°N)	Long. (°E)	Elv. (m)	Period of operation	N_{RF}	H (km)	V_p/V_s	σ
East Dharwar Craton								
MBN	16.87	77.66	417	01/1999–07/2000	58	34.40 ± 0.11	1.754 ± 0.004	0.259
AMT	16.34	75.89	542	02/2009–04/2010	54	35.80 ± 0.22	1.718 ± 0.010	0.244
ARK	16.27	76.95	487	05/2009–09/2011	21	33.95 ± 0.41	1.760 ± 0.018	0.262
APT	16.39	78.67	453	07/2009–08/2011	47	32.05 ± 0.64	1.800 ± 0.019	0.277
UKD	14.99	77.25	474	07/2009–05/2011	15	33.70 ± 1.16	1.770 ± 0.020	0.266
PKD	14.06	77.64	545	05/2009–05/2011	53	35.40 ± 0.14	1.758 ± 0.005	0.261
KDR	14.18	78.16	453	07/2000–06/2001	7	40.05 ± 2.33	1.758 ± 0.005	0.261
MCR	13.69	78.24	635	02/2009–01/2011	32	37.20 ± 3.76	1.720 ± 0.097	0.245
GBA	13.56	77.36	681	09/1998–11/2001	91	35.00 ± 0.14	1.746 ± 0.006	0.256
BGL	13.02	77.57	791	09/1998–09/2000	30	34.90 ± 0.20	1.758 ± 0.007	0.261
KOL	12.95	78.25	803	01/2001–08/2001	9	33.80 ± 0.47	1.745 ± 0.017	0.256
SLR	13.14	79.45	141	02/2009–01/2011	37	37.00 ± 0.35	1.732 ± 0.006	0.250
VBD	12.96	78.54	382	02/2009–01/2011	–	–	–	–
Cuddapah Basin								
SLM	16.10	78.89	368	11/1998–06/2000	27	33.90 ± 0.39	1.772 ± 0.015	0.266
TDT	14.84	77.91	276	03/2009–08/2011	9	35.90 ± 0.89	1.756 ± 0.027	0.260
CUD	14.48	78.77	150	05/1999–08/2001	43	35.55 ± 0.17	1.740 ± 0.009	0.253
Closepet Granite								
HPT	15.28	76.32	538	02/2009–03/2010	27	36.00 ± 0.49	1.725 ± 0.016	0.247
HGL	14.74	76.71	564	03/2011–08/2011	20	34.35 ± 0.79	1.800 ± 0.026	0.280
TMK	13.34	77.19	842	07/2000–11/2001	13	35.70 ± 0.87	1.770 ± 0.021	0.266
NTR	13.30	76.90	712	11/2001–01/2002	7	40.40 ± 1.32	1.762 ± 0.035	0.262
TGH	12.96	77.35	807	04/2009–04/2010	43	36.90 ± 0.29	1.720 ± 0.008	0.245
Kaladgi Basin								
BGM	16.12	74.65	658	02/2009–08/2011	14	48.60 ± 0.47	1.720 ± 0.011	0.245
Western Dharwar Craton								
SUP	15.26	74.54	536	05/2009–03/2011	18	37.90 ± 0.32	1.768 ± 0.013	0.265
MST	13.68	75.04	589	05/2009–03/2011	7	39.70 ± 5.11	1.728 ± 0.009	0.248
BDT	13.74	75.63	637	02/2009–01/2011	15	37.95 ± 0.26	1.728 ± 0.009	0.248
BNR	13.38	75.46	753	03/2011–08/2011	15	36.55 ± 0.16	1.718 ± 0.008	0.244
DHR	15.43	74.98	679	08/2001–05/2002	7	44.30 ± 8.36	1.768 ± 0.013	0.265
GDG	15.29	75.59	726	03/2011–08/2011	40	44.35 ± 0.21	1.732 ± 0.008	0.250
JOG	14.22	74.81	497	03/2011–08/2011	17	44.50 ± 0.44	1.740 ± 0.16	0.253
HVR	14.84	75.37	615	02/2009–03/2011	37	45.50 ± 0.12	1.720 ± 0.020	0.245
DVR	14.39	75.96	614	05/2009–01/2011	64	37.95 ± 2.39	1.785 ± 0.065	0.271
HYR	13.88	76.49	661	02/2009–03/2011	10	46.50 ± 1.06	1.728 ± 0.009	0.248
TPT	13.27	76.54	785	07/2000–12/2001	38	46.80 ± 0.13	1.732 ± 0.003	0.250
NLR	12.95	76.75	789	02/2009–08/2011	20	46.05 ± 5.93	1.732 ± 0.003	0.250
SKP	12.92	75.77	947	02/2009–01/2011	12	46.70 ± 0.45	1.830 ± 0.019	0.287
HSN	12.83	76.06	792	07/2000–12/2001	20	46.15 ± 0.34	1.755 ± 0.008	0.260
KSL	12.49	75.91	796	06/2001–12/2001	13	53.60 ± 2.11	1.755 ± 0.003	0.260
SUL	12.53	75.47	107	01/2011–08/2011	36	47.95 ± 0.14	1.810 ± 0.008	0.280
MYS	12.31	76.62	697	12/2001–06/2002	7	48.60 ± 4.86	1.830 ± 0.050	0.287
GDP	11.79	76.65	843	03/2009–04/2010	16	49.35 ± 5.51	1.760 ± 0.110	0.262
Western Ghats								
MLN	16.05	73.50	52	02/2009–08/2011	11	41.85 ± 0.56	1.836 ± 0.011	0.289
ANK	14.63	74.33	22	03/2011–08/2011	11	39.50 ± 0.016	1.740 ± 0.016	0.253
MGL	12.91	74.90	99	02/2009–08/2011	21	40.95 ± 0.25	1.806 ± 0.009	0.279
KNR	11.84	75.42	49	01/2009–01/2011	20	43.52 ± 0.28	1.810 ± 0.013	0.280
KZD	11.29	75.87	39	04/2010–02/2012	12	43.20 ± 0.55	1.775 ± 0.012	0.268

Table 1. (Continued.)

Stn. code	Lat. (°N)	Long. (°E)	Elv. (m)	Period of operation	N_{RF}	H (km)	V_p/V_s	σ
Southern Granulite Terrain								
MTD	11.78	76.01	542	02/2009–08/2011	8	50.30 ± 0.79	1.740 ± 0.015	0.253
CBR	11.27	76.94	348	04/2010–05/2011	24	46.20 ± 0.45	1.755 ± 0.018	0.260
HNR	12.13	77.39	594	02/2011–04/2012	61	45.60 ± 0.40	1.774 ± 0.009	0.267
ATR	11.60	77.54	280	05/2011–04/2012	5	47.20 ± 1.90	1.690 ± 0.035	0.230
YCD	11.78	78.21	1374	02/2009–02/2011	14	46.50 ± 2.69	1.730 ± 0.020	0.249
NKL	11.14	78.22	163	04/2010–05/2011	26	45.50 ± 0.48	1.712 ± 0.017	0.241
PBR	11.29	78.86	130	04/2010–04/2012	34	40.05 ± 3.68	1.730 ± 0.020	0.249
KKL	11.65	78.83	155	02/2009–04/2010	21	38.75 ± 0.29	1.730 ± 0.020	0.249
UTR	10.95	77.50	267	05/2011–04/2012	5	44.75 ± 0.13	1.742 ± 0.012	0.254
THR	10.70	76.47	61	02/2011–04/2012	7	44.45 ± 0.55	1.716 ± 0.012	0.243
MPR	10.53	78.40	212	01/2011–04/2012	58	41.80 ± 0.24	1.690 ± 0.012	0.231
Madurai Block/Kerala Khondelilite Block								
KOD	10.23	77.47	2335	04/2010–05/2011	40	43.20 ± 0.24	1.748 ± 0.006	0.257
MVT	09.95	76.53	151	02/2011–03/2012	53	37.50 ± 4.31	1.760 ± 0.076	0.261
ELP	09.60	76.97	1114	05/2011–03/2012	16	38.40 ± 0.41	1.765 ± 0.012	0.264
AKT	09.48	78.01	98	01/2011–04/2012	–	–	–	–
MVK	09.21	76.56	14	01/2011–03/2012	7	38.80 ± 2.31	1.710 ± 0.030	0.240
TKS	09.02	77.25	215	01/2011–03/2012	55	36.70 ± 0.17	1.770 ± 0.002	0.266
TYD	08.65	77.09	153	05/2011–03/2012	5	32.50 ± 0.47	1.745 ± 0.032	0.255
TRV	08.51	76.96	64	05/2000–06/2002	4	35.20 ± 0.33	1.730 ± 0.009	0.250
NGC	08.20	77.38	49	01/2011–03/2012	43	34.40 ± 0.05	1.740 ± 0.003	0.253
Eastern Ghats								
MGR	16.46	80.50	32	05/2010–08/2011	21	47.10 ± 0.32	1.726 ± 0.010	0.247
PMR	15.10	79.37	123	05/2009–08/2011	17	39.50 ± 0.36	1.760 ± 0.015	0.262
PDR	14.30	79.64	77	02/2009–08/2011	18	29.50 ± 0.27	1.760 ± 0.015	0.262
MDR	13.07	80.25	15	05/2000–12/2000	8	38.80 ± 2.14	1.760 ± 0.015	0.262
PDC	12.02	79.85	37	05/2009–01/2011	–	–	–	–

The WDC is made of 3.3–3.0 Ga gneisses and greenstone with enclaves of 2.5 Ga granite. Southern part of the WDC hosts 3.36 Ga greenstone belts while the northern part constitutes the 2.6 Ga Dharwar Basins. The WDC shows increasing degree of metamorphism and exposes rocks from 3–5 Kb and 500°C (greenschist facies) in north (at 15°N) to 8 Kb and 800°C (granulite facies) at 13°N in south corresponding to tectonic upliftment and erosion of 5 km in north to ~20 km in south, respectively. The WDC in the north is covered by Proterozoic Kaladgi Basin (KB) and Bhima Basin (BB) and the Deccan volcanics (DVP). The western part of the WDC is bounded by the Western Ghats (WG), an escarpment formed during separation of India from Madagascar at ~90 Ma. The EDC is dominated by late Archean (2.5–2.7 Ga) calc-alkaline complex of juvenile and anatectic granites, granodiorites and diorites (Drury *et al.* 1984; Bouhallier *et al.* 1995; Chadwick *et al.* 2000) and is also termed as Dharwar batholiths. The EDC is in thrust contact with the Proterozoic Cuddapah Basin (CB) and the Eastern Ghat Granulite Terrain (EG).

The craton progressively transitions in south into Archean metamorphic terrain (2.6 Ga), widely known as the Southern Granulite Terrain (SGT). The granulites are dissected by the well-mapped Moyar and Bhavani shear zones (MSZ/BSZ) in north and the Noyil-Kaveri shear zone (NKSZ) in south. The Pan-African terrain of southern India occur south of the NKSZ and are comprised of northern Madurai Block (MB) and southern Kerala Khondalite Belt (KKB) separated by NNW–SSE Achankovil Shear Zone (ASZ) (figure 1). These two terrains, whilst they have both suffered similar granulite facies metamorphism at ~600 Ma (Raith *et al.* 1983, 1997; Drury *et al.* 1984), belong to two distinctly different protoliths distinguished by the existence in Kerala block, of extensive deposits of deep shale sequences overlying a possibly Archean basement, subsequently granulitized to khondalites.

Our present understanding of the nature of the crust beneath the South India shield is largely based on the seismic wave velocity derived from the modelling of wide angle reflection and refraction measurements along two profiles, surface

wave and receiver function approach from a few broad-band seismograph locations. Using seismic reflection/refraction data across the WDC/EDC, Kaila and Krishna (1992) found Moho depth varying from 34 km in the east to 41 km in the west. Inversion of Rayleigh wave phase velocity in the eastern part of the shield suggests an average crustal thickness of 35 km (Mitra *et al.* 2006). Receiver function modelling studies from a few broad-band seismographs (Gaur and Priestley 1996; Rai *et al.* 2003; Sarkar *et al.* 2003; Gupta *et al.* 2003a, b; Jagadeesh and Rai 2008; Kiselev *et al.* 2008; Julia *et al.* 2009) suggest a felsic and transparent crust beneath the eastern part of the shield (EDC) in contrast with a layered crust beneath the western part (WDC). Also, eastern part of the shield is characterized by Moho at ~ 35 –38 km while the western and southern parts have Moho depth varying from 42–55 km. They also found average V_p/V_s ratio variation of 1.65–1.76 in South India. A lower Poisson's ratio (0.25–0.28) than that expected for a high-grade metamorphic terrain indicates a felsic to intermediate crust beneath the SGT (Gupta *et al.* 2003a). Receiver function modelling from two stations in the SGT shows crustal thickness and V_p/V_s ratio variation of 43.5 ± 0.7 km and 1.753 ± 0.015 for station KOD and 36.5 ± 0.9 km and 1.722 ± 0.017 for station TRV that correspond to felsic to intermediate composition respectively (Rai *et al.* 2008). Modelling of gravity field study also shows Moho depth variation of 33–48 km in SGT with the maximum of 53 km beneath the Nilgiri hills (Kumar *et al.* 2011).

4. Receiver function data analysis

For the first time, adequate coverage of the broad-band seismic stations (70 nos.) has been made to study the nature of Moho and average V_p/V_s ratio, beneath the individual seismograph location in South India. Most of these stations (55 nos.) operated during 2009–2012; the other 15 are part of an earlier experiment during 1998–2002 (Gupta *et al.* 2003a, b). Those 55 stations were operated in two phases in leap-frog mode with at least 10 stations common to both the periods. Details of their location and other results are presented in table 1. Each station consists of Guralp CMG3T/3ESP sensor with flat response between 0.0083/0.025 and 50 Hz and a Refraction Technology data logger. Data were continuously recorded at 20 samples/s. We used over 4000 three-component seismograms from earthquakes in the epicentral distance range 30° – 95° , and magnitude greater than 5.5, with clear *P*-wave arrivals. These are used to model

the crustal parameters following receiver function approach.

4.1 Methodology

When seismic waves strike an interface between two media, they are reflected and/or refracted following the Snell's law. Apart from refraction and reflection, *P*-to-*S* conversion also takes place at the interface. In the case of plane interfaces in isotropic media, only conversions between *P*- and *SV*-waves (polarized in the plane of refraction/reflection) occur, but for anisotropic media or dipping interfaces, *SH*-waves (polarized perpendicular to the plane of refraction/reflection) are also generated. Since *S*-waves propagate slower than *P*-waves, the converted phases arrive within the *P*-wave coda following the direct *P*-onset. The time difference

Figure 2. (a) Radial receiver function time series computed from deconvolution of vertical seismogram from the radial seismogram. (b) Ray diagram of different phases.

between the onsets can be used to determine the depths where the conversions occurred. Receiver function analysis model the amplitude and time of *P*-to-*S* converted phases (*Ps*) and reverberations associated with interfaces beneath the recording site. For events more than 30° epicentral distance, *P*-waves are steeply incident and dominate the

Figure 3. Epicenter locations of the earthquakes (red circles) of magnitude greater than 5.5, recorded by station AMT (black triangle).

vertical component, whereas *Ps* are contained on the horizontal components of ground motion. The amplitude of the arrivals in a receiver function depends on the incidence angle of the impinging *P*-wave and size of the velocity contrasts generating the conversion (*Ps*) and multiples (*PpPms*, *PpSms*, etc.). The arrival times of converted phase and multiples depend on the surface and the *P*-wave incidence angle and ray parameter. Figure 2 shows the phases that arrive at a seismic station as a result of interaction with a single crustal layer over a half space, and the corresponding radial receiver function obtained by deconvolving vertical component with the radial component. In the frequency domain, this can be written:

$$H(\omega) = \frac{R(\omega)}{Z(\omega)}, \quad (1)$$

where ω is the angular frequency $2\pi f$. $Z(\omega)$ and $R(\omega)$ are the Fourier transforms of the vertical and radial seismograms. $H(\omega)$ is the Fourier transform of the receiver function.

We used earthquakes of magnitude greater than 5.5 from epicenter distance between 30° and 95° to avoid multiple arrivals in the direct *P*-wave occurring at distances less than 30° caused due to triplication and also complication at distances greater than 95° resulting from core mantle boundary. Due to geographical location, the data availability for stations is azimuthally skewed with most of the earthquakes from north to east directions. This is demonstrated in figure 3 showing earthquake distribution for a typical station AMT. Seismograms

Figure 4. Quality of receiver functions (A, B or C) at three representative stations GBA, APT and NLR, respectively. Quality A refers to: clear *P*-to-*S* conversion (*Ps*) and multiples (*PpPms*, *PpSms*); B: clear *Ps* and *PpPms* or *PpSms*, and C: only clear *Ps*. Red and blue circles denote the epicentral distance and backazimuth values for individual receiver function.

corresponding to these events are checked visually and only those with clear P arrival are filtered using Butterworth high pass filter with a corner frequency of 0.02 Hz. The P arrival on the seismogram is marked with respect to the IASP91 velocity model (Kennett and Engdahl 1991) using Taup-Tool-kit (Crotwell *et al.* 1999). We used 150 s of the waveform (30 s prior to P arrival and 120 s post length) and removed the mean (DC effect) and trend (tilt in the base line) from the seismograms. Horizontal components (north/south and east/west) are rotated into the great circle path to obtain radial (perpendicular to vertical and directed towards the source) and transverse components (perpendicular to both vertical and radial components). Finally, vertical component is deconvolved from both radial and transverse components using iterative time domain deconvolution with 200 iterations (Ligorria and Ammon 1999). In this method, at first, the vertical component is cross-correlated with the radial component to

estimate the lag of the first and largest spike in the receiver function (the direct P phase). Then the convolution of the current estimate of the receiver function with the vertical component seismogram is subtracted from the radial component seismogram, and the procedure is repeated to estimate other spike lags and amplitudes. With each additional spike in the receiver function, the misfit between the vertical and receiver function convolution and the radial component seismogram is reduced, and the iteration halts when the reduction in misfit with additional spikes becomes insignificant.

A Gaussian filter of width (Gw) 1.6 is used during the deconvolution to select the most appropriate frequency band (<0.8 Hz). We preferred Gaussian width of 1.6 since the receiver function for higher Gaussian width had more noise, while those with lower Gaussian width are smoother. For detailed analysis, we selected over 1600 receiver functions with more than 80% waveform fit, from an initial nearly 4000 receiver functions. A closer

Figure 5. Quality of receiver functions computed at individual station in the study region along with topography. Thick lines show the locations of three profiles (AA', BA' and CC'), along which CCP depth migrated receiver functions are plotted in figure 10. Stations circled are used in figure 13.

examination of receiver functions from all the stations suggest three categories of seismograph locations representing the underlying geological complexity: (a) with clear P to S conversion (Ps) and multiples ($PpPms$, $PpSms$); (b) clear Ps and $PpPms$ (or $PpSms$) and (c) only clear Ps . Example of these three classes of receiver functions from seismograph location is shown in figure 4. Due to poor quality receiver functions for three stations, namely; PDC, VBD and AKT, we categorize them in F and are not included in our study. Using these criteria, distribution of quality seismograph location in South India is presented in figure 5.

4.2 Crustal parameter estimation: H - k stacking method

To obtain Moho depth (H) and average Vp/Vs ratio (k) (or Poisson's ratio σ) we used H - k stacking technique of Zhu and Kanamori (2000) which exploits the fact that arrival times and amplitude of specific Moho converted phases and multiples appearing on radial receiver functions are determined by known functions of Moho depth (H), k and average Vp in the crust. Since travel times used for crustal receiver function analysis are much less sensitive to Vp than to Vs (Zhu and Kanamori 2000), we assume an average Vp for the entire crust from previously obtained active source studies in that region. For a near true combination of H and k values, the quantity $S(H, k)$ is defined as the

weighted sum of the receiver function amplitudes at the calculated times of predicted arrivals of Ps , $PpPms$ and $PpSms+PsPms$ phases would expected to be maximum.

$$S(H, k) = \sum_{j=1}^N [w_1 r_j(t_1) + w_2 r_j(t_2) - w_3 r_j(t_3)], \quad (2)$$

where $r_j(t)$ is the amplitude of receiver function for the j th event, t_1 , t_2 , t_3 are predicted Ps , $PpPms$ and $PpSms+PsPms$ arrival times corresponding to Moho depth H and k , and N being the total number of receiver functions. The w_i 's are weighting factors, and $\sum w_i = 1$ and

$$t_1 = H \left[\sqrt{Vs^{-2} - p^2} - \sqrt{Vp^{-2} - p^2} \right] \quad (3)$$

$$t_2 = H \left[\sqrt{Vs^{-2} - p^2} + \sqrt{Vp^{-2} - p^2} \right] \quad (4)$$

$$t_3 = 2H \sqrt{Vs^{-2} - p^2} \quad (5)$$

where w_1 , w_2 and w_3 are chosen to balance the contribution from the three phases in receiver function. Among the phases, Ps having higher amplitude over $PpPms$ and $PpSms$ is given higher weight than the other two. We also set $w_1 > w_2 + w_3$ because the later two phases have similar slope in H - k plane. In this computation, we set $w_1 = 0.6$, $w_2 = 0.3$ and $w_3 = 0.1$. We perform a grid

Figure 6. Stacked radial receiver functions for stations in South India, grouped according to their geological/structural proximity.

search through H and k parameter space, and the parameter value corresponding to the maximum value of $S(H, k)$ can be considered as the best estimate.

Based on the modelling of several refraction profiles and receiver function analysis in South India (Kaila and Krishna 1992; Sarkar et al. 2001; Gupta et al. 2003a) average crustal P wave velocity (V_p) is chosen to be 6.45 km/s. H and k are allowed to vary from 20–60 km (with 0.05 km increment) and 1.6–2.0 (with 0.002 increment), respectively. For stations where the multiples (in particular, $PpPms$) are not clear, V_p/V_s ratio is taken from the neighbouring station. Poisson's ratio, which is a more useful tool to provide crustal composition than either V_p or V_s alone (Christensen 1996) can be calculated using,

$$\sigma = 0.5 \left[1 - \frac{1}{(V_p^2/V_s^2) - 1} \right]. \quad (6)$$

Parameters (H and k) uncertainty on H – k stacking methods are estimated by using bootstrap

method (Efron and Tibshirani 1986). From the entire set of receiver functions belonging to a station, receiver functions are chosen randomly with repetition. From the randomly selected receiver functions, 50 bootstrap samples are created. From each set of 50 bootstrap samples, H and k bootstrap values are calculated by using above-mentioned technique. Uncertainties are calculated from 50 bootstrap values, using the following equation,

$$\sigma_{\text{boot}} = \left[\frac{1}{n-1} \sum_{i=1}^n (X_i - X_{\text{avg}})^2 \right]^{1/2}, \quad (7)$$

where X_i is the bootstrap value of a quantity (H or k) and X_{avg} is the average bootstrap value of the quantity. In addition, for assessing uncertainty in H and k resulting from the choice of the average crustal V_p , the H – k stacks are recomputed using V_p of 6.35 and 6.55 km/s. For the variation of V_p for 6.35 and 6.55 km/s, maximum variation of ~ 1.5 km and ~ 0.01 are observed in H and k , respectively.

Figure 7. Moho converted P_s phase time for each station contours at every 0.25 s and annotated at every 0.5 s. Seismograph stations (black triangles) and major tectonic features (solid lines) are also shown.

4.3 Common Conversion Point (CCP) stacking and depth migration

The H - k stacking method provides an average crustal thickness and V_p/V_s ratio over an area with radius varying from 15–65 km assuming that

the earth is flat layered and represented by a 1D velocity model. To study the lateral variability, depth migration of receiver functions is carried out using the Common Conversion Point (CCP) method (Dueker and Sheehan 1997). The amplitudes for each receiver function are back-projected

Figure 8. H - k stacking results for selected stations with varying quality of receiver functions. (a) H - k stacking results for the stations along their respective values and the corresponding errors are shown on the top right corner. White circle corresponds to the optimal values of H and k . (b) Receiver functions used for H - k stacking (as shown in a). Red, blue and magenta dashed lines correspond to the P_s , P_pP_{ms} and P_pS_{ms} timings, respectively, calculated using the optimum value of H and k values. (c) Epicentral distance (red circle) and backazimuth (blue circle) values for individual receiver function are plotted in panel (b).

along a ray-path calculated for standard IASP91 model. This involves the following steps:

- Computation of the geographical locations of the piercing points of all P -to- S conversions for each source–receiver pair at 1 km depth interval from 1 to 100 km, using the IASP91 reference velocity model (Kennett and Engdahl 1991); and
- calculation of the travel times of P -to- S converted phases from various depths using the relation:

$$T_{Pds} = \int_{-d}^0 \left[\sqrt{V_s(z)^{-2} - p^2} - \sqrt{V_p(z)^{-2} - p^2} \right] dz, \quad (8)$$

where p denotes the ray parameter for the P wave, d the depth of the discontinuity and $V_p(z)$ and $V_s(z)$ are the P and S wave velocities at depth z (Gurrola et al. 1994; Dueker and Sheehan 1997), respectively. The volume along a profile is divided into block of 1 km height and length but with a wider dimension perpendicular to the profile. Amplitudes of the rays traversing each bin are summed and averaged to have amplitude at that bin using the relation:

$$A(d) = \frac{1}{N} \sum_{i=1}^N A_i(T_{Pds}^i), \quad (9)$$

where $A(d)$ is the stacking amplitude for a candidate discontinuity at depth d , N is the number

of receiver functions piercing particular depth d , $A_i(T_{Pds}^i)$ is the amplitude of the i th receiver function at time T_{Pds}^i , and T_{Pds}^i is the travel times of P -to- S converted phases of the i th receiver function at depth d . It has been shown that a 4% change in the V_p/V_s ratio can perturb the crustal thickness by 3 km, whereas the same percentage change in V_p would cause an error of the order of only 1 km (Zhu and Kanamori 2000).

5. Results

5.1 Nature of the crust

To study the nature of Moho conversion in P_s phase and other intra-crustal conversion phase, we stacked receiver function for individual stations in narrow epicenter and backazimuth ranges. Figure 6 shows stacked receiver function of individual stations arranged by different geological blocks of South India Shield, which show remarkable spatial coherence of Moho converted P_s phase with the surface geology and compositional boundaries. Important observations from the receiver function data include: the stations in the late Archean EDC and the Proterozoic CB are characterized by P_s time ~ 4.5 s, CG have P_s time of 4.5–5 s and almost no intra-crustal conversion. P_s time in the WDC is ~ 5 –6 s, EG ~ 4.5 –5.6 s, WG ~ 4.7 –5.7 s and SGT ~ 3.7 –6 s with significant presence of intra-crustal conversion. P_s timings in the northern part of WDC is ~ 4.3 s compared to >5 s in south. The

Figure 9. (a) Moho depth, and (b) V_p/V_s ratio variation maps of South India using H - k stacking method. Stations (black triangles) and tectonics (solid lines) are also projected on the plots.

stations in Archean SGT (north of NKSZ) have P_s time >5 s while the stations in Neo-Proterozoic MB/KKB have P_s time ~ 4.5 s. The time of Moho-converted P_s phase from individual station is contoured in figure 7. Largest Moho-converted P_s time (>6 s) is observed beneath mid-Archean greenstone belt in the southern part of WDC. Considering $V_p \sim 6.4$ km/s and $V_s \sim 3.7$ km/s, and ray parameter $p \sim 0.0576$ s/km, corresponding to epicentral distance of 67° , we find that 1 s of t_1 (P_s arrival) corresponds to ~ 8 km Moho depth (H) variation (using equation 3). We, therefore infer significant Moho depth variations (upto 10 km) among the different geological provinces of South India.

H - k results for few stations from different geological provinces along with observed receiver function and theoretical P_s (red dashed line), P_pPms (blue dashed line) and $PpSms$ (magenta dashed line) timings calculated from optimum value of H and k are presented in figure 8. To examine the regional variation of Moho depth (H) and k in the South India Shield, we collected these parameters for each station, and interpolated over a 10×10 km grid using Generic Mapping Tools (Wessel and Smith 1998). Moho depth and V_p/V_s ratio variations are shown in figure 9. Details of individual station are presented in table 1. The EDC with surface topography of 400–600 m, has Moho

Figure 10. Common Conversion Point (CCP) depth migrated receiver function along three profiles (shown in figure 5). V_p/V_s ratio (red star) and Moho depth (white star) obtained from H - k stacking methods are projected on each plot. Red dashed lines are the boundary between two geological provinces.

depth of ~ 32 – 38 km. Despite having similar topography as EDC, WDC shows large variation in the Moho depth: 38 – 46 km in north and 46 – 54 km in its south. Using normal density contrast across Moho, this should lead to an elevation of more than 3 km in the southern part of WDC. However, in view of the nearly flat topography (~ 600 m), we speculate that the region is compensated by high density (and high velocity) material in the lower-most crust. In the northern part of SGT (north of NKSZ), Moho depth varies from 39 – 50 km, while in MB/KKB, it varies mostly from 33 – 39 km. In EG and WG, Moho depth varies from 39 – 47 km, 40 – 43 km, respectively. Interestingly we observe similar V_p/V_s ratio (~ 1.72 – 1.76) in EDC, EG and CG, and higher V_p/V_s ratio (~ 1.73 – 1.83) in WG and WDC. In northern part of SGT, V_p/V_s ratio mostly varies from 1.69 – 1.75 , while in MB/KKB, it varies from 1.71 – 1.76 .

CCP depth migrated section with V_p/V_s ratio along three profiles (shown in figure 5: N–S profile AA' and BA', W–E profile CC') are presented in figure 10. To compare the Moho depth computed from two different approaches, Moho depth calculated from H – k methods are projected on the CCP plot. Figure 10 shows a clear agreement between both the methods. Due to limited backazimuthal coverage with most of the arrivals from the NE and SE directions and station density along the profile, it has not been possible to provide continuous coverage of the Moho. Ideally, to have well defined continuous image of Moho, the stations separation should be 15 – 20 km. Nevertheless, the Moho with most prominent signal is clearly visible in all the profiles. Two N–S profiles AA' and BA' passing through the WDC and EDC to SGT show clear Moho deepening in southern part of the WDC reaching over 50 km; northern SGT with Moho depth of ~ 45 km compared to ~ 38 km Moho beneath MB/KKB. We also observe negative phase (red colour) in few stations in the MB/KKB. This is further discussed in the next section. The profile CC' through the oldest part of the craton (greenstone belt in the southern part of WDC) to EDC shows the thickest crust of ~ 50 km in the WDC, while in the EDC it is around ~ 37 km. Figure 10 clearly shows that CSB is the boundary between WDC and EDC.

To examine whether the topography is compensated by the change in crustal thickness, we plotted elevation against Moho depth for all the stations in figure 11(a). We do not observe any correlation between the two parameters. The lack of correlation between Moho depth and elevation indicates that variations in crustal thickness do not have a first-order influence on topography in South India and lateral variation of density is an important factor in controlling the isostatic upliftment.

Figure 11. Plots of Moho depth *versus* elevation (a), and V_p/V_s ratio (b) for all the stations of South India shield listed in table 1.

Further, absence of any clear correlation between Moho depth and V_p/V_s ratio (figure 11b) indicates the complex crustal structure in the entire region, and this can be investigated by detailed modelling of receiver function. This is beyond the scope of present investigation and is being pursued separately.

5.2 Evidence for mid-lithospheric discontinuity

Several recent studies have proposed a mid-lithospheric discontinuity of debatable origin existing under several cratons (Thybo and Perchuc 1997; Abt *et al.* 2010). This has also been revealed in several recent receiver-function studies that show negative impedance contrast at depths between 60 and 150 km (Fischer *et al.* 2010). This interface is too shallow to be regarded as the Lithosphere–Asthenosphere Boundary, but the petrological origin of this additional discontinuity and its assumed distinctness from the LAB remain uncertain. A mid-lithospheric interface has been observed by Savage and Silver (2008) at 150 km depth beneath the northeastern part of the Kalahari craton using S receiver functions that

was interpreted to mark a change in composition. They interpreted the boundary due to refertilized depleted lithosphere by basaltic melt rich in iron and volatiles possibly related to the eruption of the Karoo flood-basalt and associated magma intrusions. A mid-lithospheric velocity reduction is also detected underneath central and western Australia at a depth range between 69 and 85 km combining results from P and S receiver functions (Ford *et al.* 2010). It is assumed to represent either a change in grain size or fabric, vertical variations in mantle composition or low-velocity melt accumulation. Abt *et al.* (2010) utilized P and S receiver functions as well velocity profiles derived from surface wave data from United States. They

reported a similar discontinuity at depth between 59 and 113 km beneath the cratonic core and certain Phanerozoic regions of the United States. The authors proposed alteration of the cratonic lithosphere by melt or the lower boundary of an ancient, highly depleted layer of the lithosphere to explain the observed interface. S receiver functions have further revealed the existence of a mid-lithospheric discontinuity beneath the Canadian Shield (Miller and Eaton 2010). Recent studies by Wolbern *et al.* (2012) have also shown the evidence of the discontinuity under the Tanzanian craton at depth of 50–100 km from S receiver functions. Kumar *et al.* (2007) reported low velocity at a depth of 80–100 km at a few locations in India based on the

Figure 12. Receiver function plot for (a) sharp negative phase and (b) weak negative phase observed at ~10–12 s. RFs are plotted with increasing epicentral distance (DEL, in degree) from eight seismograph stations. Negative phase is marked by red dashed line.

Figure 13. Location of seismograph stations where negative phase (LVZ) is observed. Stations with sharp and weak negative phase observed are marked by red and blue triangles, respectively.

analysis of S receiver functions and interpreted it as due to shallow LAB.

While analysing receiver functions, we observed a negative phase between 10 and 12 s at several locations in South India both in the mid Archean segments and Neo-Proterozoic terrain of South India. We present the receiver functions at selected stations and mark the negative phase (figure 12a, b), which corresponds to a source depth of 80–100 km. The negative polarity could be a converted phase from velocity inversion or may be a multiple arising from a shallower interface. These could be discriminated based on the arrival time–distance relation. For a converted phase from a depth, the arrival time decreases with the epicenter distance while for a seismic phase reverberating from this depth the time of arrival would increase with the distance. We examined all the dataset using this criterion and concluded that the observed phase at ~10–12 s is conversion from the top of low velocity layer. Conversion of this negative P to S phase at 10–12 s, in terms of depth suggests the presence of low velocity at ~85–100 km. Figure 13 shows location of seismic stations where such LVZ is observed. The LVZ is sharp and consistent in the Neo-Proterozoic domain affected by the Pan-African event (Rai et al. 2008).

6. Discussions and conclusions

Global review of seismic structure suggests that the Proterozoic crust has a thickness of 40–50 km, while Archean crust is only 27–40 km thick (Durrheim and Mooney 1994). Alternatively, Rudnick and Fountain (1995) and Tugume et al. (2012) suggested that both Archean and Proterozoic crusts have similar crustal thickness (37–45 km). Zandt and Ammon (1995) using data distributed across the globe, found crustal thickness of shields and platforms to be between ~37 and 42 km and V_p/V_s ratio to be 1.78. Chevrot and van der Hilst (2000), using broad-band receiver function measurements from Australia, found no significant variation in V_p/V_s ratio between the Archean and Proterozoic crust. However, thickness of the crust shows remarkable variability from thinner Archean crust (~35 km) to a thicker Proterozoic crust (~45 km). Detailed analysis of observations from South African Seismic Experiment (Nguuri et al. 2001; Nair et al. 2006) shows undisturbed Archean crust (Zimbabwe and Kaapvaal cratons) having thinner crust (38 km) and lower V_p/V_s ratio (1.73), compared with a thicker crust (~43 km) and higher V_p/V_s ratio (~1.78) for a disturbed Archean terrain (Bushveld mafic complex). Seismological measurements from the Canadian Shield (Thompson et al. 2010) suggest transparent and felsic crust ($V_p/V_s \sim 1.73$) with sharp Moho at 35–40 km depth beneath the mid-Archean (3.2–3.6 Ga) and late (2.5–2.8 Ga) Archean crustal domains.

We find Moho depths, 32–38 km in the late Archean EDC and CG, 34–36 km in the proterozoic CB, 38–46 km in the 2.7–3 Ga Dharwar Basin, ~39–50 km in the Archean SGT and 33–39 km in the Pan-African belt. The thickest crust (~54 km) is observed in the mid-Archean greenstone belt in the southern part of WDC. The crustal thickness estimate for the late-Archean EDC is similar to the global average (30–40 km). The mid-Archean nucleus in WDC is, however, considerably (>10 km) thicker than that of an average Archean Shield and is at variance with the hypothesis that older crust was thinner.

Compressional wave velocity has been widely used to infer the composition of the crust. However, availability of three-component seismic measurements of earthquake waveform allow us to place tighter constraint on the crustal composition using V_p/V_s ratio instead of velocity of either P or S wave alone. Average crust V_p/V_s ratio is dependent on the cracks, porosity, temperature, and mineralogy of the rock. At higher pressure, ~200 MPa, laboratory measurements suggest that it essentially depends on the silica content in the rock – higher V_p/V_s ratio for a more mafic crust

(Christensen 1996). For the common igneous and metamorphic rocks, it is controlled by the relative presence of quartz ($V_p/V_s \sim 1.49$) and plagioclase ($V_p/V_s \sim 1.87$). For common rock type, V_p/V_s ratio varies from 1.63 to 2.08. For lower crustal rocks, low V_p/V_s ratio (<1.76), intermediate V_p/V_s ratio (1.76–1.81) and high V_p/V_s ratio (>1.81) are characteristic of felsic, intermediate and mafic composition, respectively. For example, granite rock has a characteristic V_p/V_s ratio of 1.71, while for intermediate composition rocks (e.g., diorite) it is 1.78, and for mafic rocks (e.g., gabbro) 1.87 (Christensen 1996). We observe V_p/V_s ratio ~ 1.7 – 1.76 in most parts of the South India, which suggests felsic to intermediate crust. The exception being the part of the WG and the southern part of the WDC (greenstone belt) with $V_p/V_s > 1.81$, suggestive of mafic crust beneath them.

In summary, the exposed mid-Archean crust of western Dharwar is characterized by thick (~ 50 km) and average mafic composition in contrast with a thinner and felsic crust in late-Archean and Proterozoic terrains. Considering a ~ 15 km depth of burial of rocks currently expose on surface in the WDC, we speculate a Himalaya–Tibet like crustal thickness of ~ 70 km beneath the mid-Archean crust. Presently, the Dharwar Craton has almost flat topography. This is possible due to presence of mafic crustal root beneath the south WDC as also reflected in high average V_p/V_s for the crust. The flat Moho and felsic crust elsewhere in South India could be a consequence of delamination of mafic lower crust.

In the shallower mantle, at depth of 85–100 km, we observe a negative polarity phase at several locations in the south India, prominently in the Pan-African granulite terrain. This could be a fossil mid-lithospheric low velocity. Pacific Ocean like subduction has been argued in the Pan-African terrain of South India (Santosh *et al.* 2009). In this framework, we examine the relevance of pervasive low velocity at depth of 70–100 km observed in the Pacific belt and its possible implication to the observed low velocity in South India. It is argued that the low velocity observed in the Pacific subduction zone is related to mineralogy of the subducted crust (Gubbins *et al.* 1994), but the specific mineralogy of the low velocity layer remain controversial and is a subject of intense research (Connolly and Kerrick 2002). The other causative sources for low velocity, discussed above remain equally debatable in the absence of any credible theoretical, experimental support. This calls for a more sustained research in petrology and mineral physics to understand the cause for such a shallow mantle low velocity in the continental interior. Equally important is to sharpen seismological tools

to image and quantify the properties of the low velocity zones.

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